REPORT DOCUMENTATION PAGE

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1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE Sept 2004	3. REPORT TYPE AND DATES COVERED Journal Article

4. TITLE AND SUBTITLE
Total energy expenditure estimated using a foot-contact pedometer

5. FUNDING NUMBERS

6. AUTHOR(S)
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8. PERFORMING ORGANIZATION REPORT NUMBER
M04-11

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Medical Research and Materiel Command
Fort Detrick, MD 21702-5007

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
Background: Total energy expenditure (TEE) assessment using pedometers provide an easy and less expensive method than doubly labeled water (DLW). This study assessed TEE by a new pedometry method (TEEpedo) compared to the doubly labeled water method (TEEdlw).
Material and Methods: Shipboard sailors (7 men, age: $23.0 + 3.9$ yrs; ht: $180.2 + 6.5$ cm; wt: $83.8 + 11.8$ kg, and 10 women, age: $24.7 + 4.4$ yrs; ht: $165.2 + 8.0$ cm; wt: $63.5 + 14.0$ kg) (Mean + SD) were studied for 8 days. The energy cost of activity was estimated using (a) total body weight, (b) foot-ground contact times [Tc] during running, walking, and non-exercise activity [NEAT], and (c) the known proportion of time spent in each activity category. Resting metabolic rate (RMR) was estimated from lean body mass.
Results: TEEpedo was calculated as: TEEpedo (MJ) = (1440 × [%Run Time × ((0.0761 × [Total Body Weight/TcRun]) - 7.598) + %Walk Time × ((0.056 × [Total Body Weight/TcWalk]) - 2.938) + (%NEAT Time × 0.1 × [RMR/Minute])] + RMR)/239. This method, explained 79% of the variance of TEEpedo with a 95% confidence interval of + 0.81 MJ/day, relative to TEEdlw ($12.55 + 3.3$MJ/day). Mean TEEpedo ($12.65 + 3.1$ MJ/day) did not differ from mean TEEdlw (p = 0.95).
Conclusion: At TEEs > 14 MJ/day, the TEEpedo method underestimated actual TEE, possibly due to unaccounted for upper body exercise. At more moderate TEEs of 9 to 14 MJ/day, the Tc pedometry method provided accurate estimates of TEE.

14. SUBJECT TERMS
humans, activity, energy expenditure, locomotion, pedometer, pedometry

15. NUMBER OF PAGES
6

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
U	U	U	U

Total energy expenditure estimated using a foot-contact pedometer

Authors' Contribution:
A Study Design
B Data Collection
C Statistical Analysis
D Data Interpretation
E Manuscript Preparation
F Literature Search
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Summary

Background: Total energy expenditure (TEE) assessment using pedometers provide an easy and less expensive method than doubly labeled water (DLW). This study assessed TEE by a new pedometry method (TEEpedo) compared to the doubly labeled water method (TEEdlw).

Material/Methods: Shipboard sailors (7 men, age: 23.0±3.9 yrs; ht: 180.2±6.5 cm; wt: 83.8±11.8 kg, and 10 women, age: 24.7±4.4 yrs; ht: 165.2±8.0 cm; wt: 63.5±14.0 kg) (Mean ±SD) were studied for 8 days. The energy cost of activity was estimated using (a) total body weight, (b) foot-ground contact times [Tc] during running, walking, and non-exercise activity [NEAT], and (c) the known proportion of time spent in each activity category. Resting metabolic rate (RMR) was estimated from lean body mass.

Results: TEEpedo was calculated as: TEEpedo (MJ) = (1440 × [%Run Time × ((0.0761 × [Total Body Weight/TcRun]) − 7.598) +%Walk Time × ((0.056 × [Total Body Weight/TcWalk]) − 2.938) + (%NEAT Time × 0.1 × [RMR/Minute])] + RMR)/239. This method, explained 79% of the variance of TEEpedo with a 95% confidence interval of ±0.81 MJ/day, relative to TEEdlw (12.55±3.3MJ/day). Mean TEEpedo (12.65±3.1 MJ/day) did not differ from mean TEEdlw (p=0.95).

Conclusions: At TEEs >14 MJ/day, the TEEpedo method underestimated actual TEE, possibly due to unaccounted for upper body exercise. At more moderate TEEs of 9 to 14 MJ/day, the Tc pedometry method provided accurate estimates of TEE.

key words: humans • activity • energy expenditure • locomotion • pedometer • pedometry

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BACKGROUND

Accurate assessment of total energy expenditure (TEE) in free-living humans is difficult [1]. For example, the intake-balance method which assesses TEE from food intake and changes in body composition requires a relatively long evaluation period [2]. The factorial method requires accurate measurement of activity duration and the correct classification of the activity [1]. This method can be imprecise when studying free-living individuals. The doubly labeled water (DLW) method of measuring TEE in humans is reliable and accurate [3], but expensive and can usually be utilized only over periods of 2 days or more.

Pedometers provide an alternative approach to estimating TEE that is easier to apply than intake-balance methods, can be readily used in field studies, and is less expensive than the DLW method. Human activity has been assessed with pedometers (through counting steps and calculating distances covered) for over 500 years [1]. Pedometers were not originally designed to quantitatively assess metabolic energy expenditure, but recently manufacturers have claimed their devices can accurately determine the energy expenditure of activity [1]. Conventional pedometers have been shown to predict actual energy expenditure with correlation coefficients ranging from r=0.46 to 0.88 during controlled laboratory studies, but few studies have assessed the validity of pedometer estimates of energy expenditure in field environments [4]. Three studies have compared pedometer measurements of energy expenditure to those made by DLW in free-living environments. One study of elderly patients with intermittent limping and restricted ambulatory movement showed a significant correlation (r=0.61; $p<0.002$) between TEE estimates provided by a Caltrac pedometer with its proprietary algorithm (Muscle Dynamic Fitness Network, Torrence, CA), and TEE measured by DLW [5]. However, non-significant relationships were reported between pedometer TEE (TEEpedo) and DLW TEE (TEEdlw) in two other studies, one with overweight women [6] and the other with young healthy adult women [7].

Hoyt and co-workers [8] have demonstrated that, knowing total weight of a volunteer (i.e, body weight plus clothing and other gear carried), a specially designed foot-ground contact monitor could accurately predict (R^2=0.93) exercise energy expenditure of men walking and running on a treadmill. The purpose of this study was to extend this work by determining if a pedometer that measured foot-ground contact time (Tc) and differentiates differences in levels of activity (no activity, non-exercise activity thermogenesis [NEAT], walking, and running) could be used to accurately estimate TEE. NEAT is comprised of non-purposeful activity such as fidgeting, shuffling, and slow movements of the feet.

MATERIAL AND METHODS

Volunteers

Twenty U.S. Navy sailors (8 men and 12 women) assigned to an amphibious assault ship that resembled a small aircraft carrier, volunteered to participate in this study. TEEdlw was measured in 17 test volunteers, while background isotopic enrichments were monitored in the three remaining volunteers (1 man and 2 women) who were given tap water rather than DLW. Monitoring background enrichments is important given that shifts in background isotopic enrichment can adversely affect the precision of TEEdlw [2,9]. The test volunteers who participated in this study gave their free and informed written consent in accordance with relevant US Army regulations regarding the use of volunteers in research. The investigators adhered to the policies for protection of human subjects as prescribed in Army Regulation 70–25, and the research was conducted in adherence with the provisions of 45 CFR Part 46. Volunteers were participating in a routine 8-day field training exercise at sea. Participants had a variety of jobs with varying levels of physical activity.

Experimental design

On Day 0, the volunteers were instrumented with pedometers, and had their age and height recorded, and were administered DLW. Body weights were obtained from volunteers in t-shirts and underwear prior to the administration of the DLW (Day 0) and at the conclusion of the study (Day 8).

Methods for assessing TEEdlw are described elsewhere [9]. Briefly, on Day 0 volunteers refrained from eating or drinking for approximately 6 hrs, and then provided an ~30 ml urine sample and ~10 ml of saliva. Volunteers then drank 0.25 g/kg of estimated total body water (TBW) of $H_2^{18}O$ and 0.18 g/kg of TBW of ^2H_2O (Isotec Inc, Miamisburg, OH), or tap water (controls). Total body water was estimated as 73% of lean body mass (LBM) [9]. Lean body mass was estimated to be 15% of body weight for men and 25% of body weight for women [10,11]. About 50 ml of the ship's drinking water was also consumed after it was used to rinse the dose container. Saliva samples (~10 ml) were collected at 3 hr and 4 hr post-DLW ingestion for TBW determinations [2,3].

First morning urine samples collected each day were used to measure isotope elimination rates for ^2H and ^{18}O. Background changes in baseline isotopic abundances due to a changed water source were measured in 3 volunteers who were given tap water rather than the labeled water. Correcting for significant changes in background enrichment improves the precision of the estimates of TEEdlw [9]. Estimated TEEdlw was obtained from the rate of CO_2 production calculated through analysis of differential isotope elimination rates using methods previously described [9]. A metabolic fuel quotient of 0.85 was assumed based on typical western diets with body fat reserves remaining stable [1]. Body energy stores were calculated by isotope dilution ($H_2^{18}O$) measurements of TBW [2]. Fat-free mass was calculated as the difference between body mass and fat mass. Fat-free mass was assumed to be 27% protein and 73% water; fat mass was assumed to be 100% fat. Energy equivalents of 0.018 MJ/g for protein and 0.040 MJ/g for fat were used [2].

Foot pedometer estimates of exercise energy expenditure were based on total weight (body and clothing weight) and Tc of the foot with the ground as measured by the accelerometers and a microprocessor within the pedometer [8]. This approach is based on the relationship that energy ex-

penditure generated during walking or running is primarily determined by the cost of supporting one's body weight and the rate at which this locomotion force is generated [12,13].

The foot-ground contact pedometer (Fitsense Technology Inc, Southboro, MA) is a small electronic device (approximately 5.8 cm × 7.6 cm × 6.4 cm; 56 g) that fits into a cloth pouch mounted to the outside of the boot or shoe through the shoelaces. Encased within the monitor are an accelerometric sensor circuit, an analog to digital converter, and a microcontroller (microprocessor, memory, real time clock, and computer interface unit). The pedometer collects information on each step and records Tc in ms. The memory can record up to 81,760 events, whether steps or records of no activity. A record of no activity can be as short as 1 sec or as long as 0.5 hr. Data can be transferred from the pedometer to a laptop computer using the manufacturer's interface unit and software (Logger Interface v 2.19; Fitsense Technology Inc, Southboro, MA). This software also identifies the different types of foot movement activity. Briefly, the pedometer provided a step-by-step estimate of Tc. The algorithm detects the accelerometric signal associated with heel impact and toe off that is generated within the sensors of the pedometer during each stride to identify the specific Tc to within ±2 ms [14]. Activity classifications of run, walk, NEAT, and no activity are determined by the pattern of the foot-ground contact waveforms [14]. The pedometer measures Tc by identifying the rapid foot de-acceleration on heel strike, and the more subtle acceleration on toe-off. Periods of no acceleration are classified as "no activity". Periods of walk and run were differentiated by the duration of Tc, with Tc of 500 ms or less classified as run and over 500 ms classified as walk [14]. NEAT periods were classified when a heel strike was detected but the subtler toe-off signal was not. These NEAT movements generally occur when movement velocity was less than 0.9 m/sec [14].

Volunteers were instructed to wear the pedometers on their shoes during the entire study. If participants changed shoes, they were instructed to move the pedometer to the new pair of shoes. Pedometer data was downloaded and batteries changed on Day 5. Pedometers were returned to participants within 30 min. Pedometer data was also downloaded on Day 8 at the conclusion of the study.

Data analysis

Descriptive statistics are reported as means (the arithmetic mean) ± standard deviations (SD). All data were analyzed using the Statistical Package for the Social Sciences (SPSS) for Windows Version 11.0 (SPSS, Inc; Chicago, IL). Analyses of variance were used to determine mean differences in TEE by method (DLW vs. pedometer) as data was normally distributed. The two pedometer data files for each volunteer (Day 0 to Day 5, and Day 5 to Day 8) were merged into a continuous data file (minus the 30 min not recorded when batteries were changed and files downloaded on Day 5). The amount of time spent in each activity (run, walk, NEAT, and no activity) was summarized. Average Tc for each of these modes of activity was calculated and specific algorithms used to estimate energy cost of activity using linear regression. A Bland-Altman plot [15] shows the difference between individual measures by the two methods plotted

against the mean of the two methods. The mean error was calculated as the standard deviation (SD) of the difference between TEEpedo and TEEdlw, while total error was calculated as $\sqrt{[\Sigma(\text{TEEpedo} - \text{TEEdlw})^2/(n-1)]}$.

TEE is composed of active energy expenditure, the thermic effect of food, and resting metabolic rate (RMR). Active energy expenditure is composed of the metabolic cost of locomotion (M_{Loco}) and NEAT. Since dietary intake was not assessed in this study, the thermic effect of food was not included in the calculation of TEEpedo. Determination of RMR was estimated using the algorithm developed by Cunningham [16] from LBM:
(Algorithm 1): RMR (kcal/day) = 500 + 22 (LBM).

The Tc data was used to estimate the amount of time spent in each category of activity (run, walk, NEAT, and no activity), and the metabolic energy cost for each activity category including the prorated portion of RMR. The original algorithm [8] to estimate M_{Loco} developed using force sensitive insoles, did not differentiate between walking and running:
(Algorithm 2): M_{Loco} in Watts, (EE(W)) = 3.701 × (Total Weight/ Tc) – 149.6

The Tc data on this study used an accelerometer instead of a force resistance technology. While the concept of Algorithm 2 of using total weight of the individual and measured Tc was applied in this study, using Algorithm 2 was invalid because of technology differences in how Tc was determined. Improved algorithms for separately estimating the metabolic cost of walking and running were developed and validated using unpublished data from Weyand and co-workers and published data gathered from a study of 14 volunteers running and walking on a treadmill [14]. These modified algorithms, developed using the same accelerometer-based Tc pedometer used in the present study (Fitsense, Southboro, MA), were:
(Algorithm 3): M_{Loco} of running, $M_{Loco\text{-}run}$ (W) = 4.517 × (Total Weight/Tc) – 378.33
(R^2=0.76, p<0.001),
and
(Algorithm 4): M_{Loco} of walking, $M_{Loco\text{-}walk}$ (W) = 4.312 × (Total Weight/Tc) – 269.62
(R^2=0.56, p<0.001),

where, total weight includes the weight of anything worn or carried, and Tc equals foot-ground contact time. These algorithms were based on regression equations that partitioned Tc into walking and running steps. Weyand et al. [14] describe in their previously published paper the pedometer waveform characteristics associated with the accelerometrically based pedometer. These algorithms (Algorithms 3 and 4) were then validated (R^2=0.89, p<0.001) with data from a study of volunteers walking and running 1300 m to 1600 m on a dirt road with loads of 13.6 kg or 27.3 kg or without a load (Weyand and co-workers, unpublished data).

The metabolic cost of NEAT, defined here as foot motion not associated with structured walking or running, was estimated as metabolic cost of standing, where the metabolic cost of standing was calculated using the non-movement portion of the Pandolf equation [17]. Based on the following rationale, the energy cost of NEAT was estimated as

Table 1. Physical characteristics of test volunteers by gender.

	Men (n=7)	Women (n=10)
Age (yrs)	23.0±3.9	24.7±4.4
Height (cm)	180.2±6.5	165.2±8.0
Pre-Study Weight (kg)	83.8±11.8	63.5±14.0
Post-Study Weight (kg)	84.3±11.0	63.1±13.4
Lean Body Mass (kg)	69.1±9.4	44.2±7.4
Body Fat (% of Body Weight)	17.3±6.5	30.7±5.2
Body Mass Index (kg/m²)	24.9±3.5	23.5±3.6

Values are expressed as mean ±SD

Table 2. Activity and total study duration, and the estimated number of steps and fraction of total number of steps associated with physical activities, including non activity thermogenesis (NEAT), walking, and running.

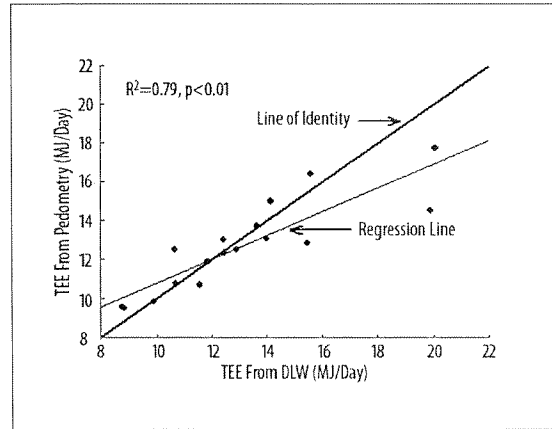|	Hours	% of total
Activity (h)	98±22	55
Inactivity (h)	80±19	45
Total hours assessed	178±24	–
Activity type and number of steps	**Steps**	**% of total**
NEAT (non-exercise activity)	16,281±8598	55
Walking	13,288±8739	38
Running	1533±1616	7
Total steps	31,102±17,821	100

Values are expressed as mean ±SD, n=17. Activity includes running, walking; NEAT – non exercise activity thermogenesis (everything that is not sleeping, eating, or volitional exercise); inactivity includes sleeping and when awake with no movement of the foot

Figure 1. Individual total energy expenditures (TEEs) assessed using doubly labeled water (DLW) and predicted from pedometry.

$0.1 \times$ RMR/min. The energy cost of standing quietly is approximately 12% to 22% above RMR. However, foot movements can occur while lying down or sitting with estimates of energy cost in these positions only 0% to 10% above RMR [18]. Therefore, a value of 0.1 times RMR/min was chosen as the value to account for NEAT. Periods when no motion was present were classified as "no activity" with energy costs equal to RMR.

The predictive algorithm is:
(Algorithm 5): TEEpedo (MJ) = (1440 × [%Run Time × ((0.0761 × [Total Body Weight/TcRun]) – 7.598) + %Walk Time × ((0.056 × [Total Body Weight/TcWalk]) – 2.938) + (%NEAT Time × 0.1 × [RMR/Minute])] + RMR)/239,
where a constant, 1440 (the number of minutes in a day) was used to obtain 24 hr TEEpedo. RMR was accounted for by adding the calculated RMR to the equation. The new predictive algorithm developed for the present study used the

same walking and running algorithms described above but converted values into kilocalories per minute to be consistent with the Cunningham equation [16]. Division by the constant 239 converted kilocalories to MJ (1 MJ=239 kcal).

RESULTS

The physical characteristics of the volunteers are shown by gender in Table 1. A summary of the time spent in activity and inactivity, and the estimated number of steps associated with physical activities, including NEAT, walking, and running and the duration and proportion of each activity are shown in Table 2. This new prediction equation, explained 79% of the total variation. The intercept (9.28) and slope of the regression line (0.61) relative to the line of identity suggests TEEpedo underestimated TEE when compared to TEEdlw when values exceeded 14 MJ/d (~3300 kcal/day). This algorithm predicts with 95% confidence TEE within ±0.81 MJ/day. Individual TEEpedo plotted against TEEdlw is shown in Figure 1. A Bland-Altman plot showing the difference between methods (TEEpedo – TEEdlw) plotted against the mean of the two measures illustrates the small bias between the two measures except for 1 data point which fell outside the two standard deviation lower limit (Figure 2). There was no significant difference in mean TEE assessed by DLW or predicted by pedometry (Figure 3).

DISCUSSION

In the present study of ship-board military personnel, the foot-ground contact pedometry method provided an accurate estimate of TEE at levels up to 14 MJ/d. At greater levels of TEE, when upper body exercise may have contributed significantly to TEE, the pedometry method underestimated TEE.

Estimates of TEEpedo were calculated using an algorithm that partitioned Tc data gathered by pedometry according to the exercise type and intensity (run, walk, NEAT, RMR), and incorporated estimated RMR. To assess the reliability of TEEpedo, estimates were compared to those determined by DLW – the scientific community's gold standard for measuring free-living TEE.
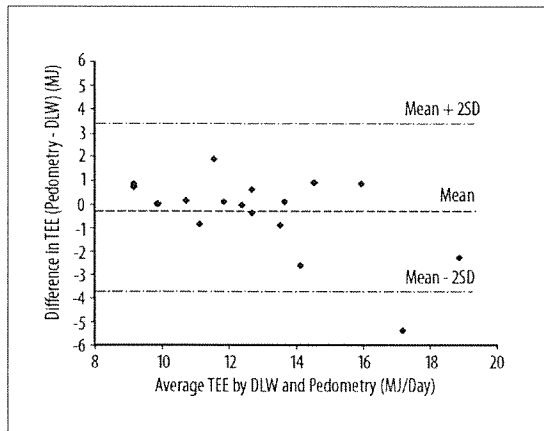
Figure 2. Bland-Altman plot showing the difference in total energy expenditure TEE between the pedometry (TEEpedo) and doubly labeled water (DLW) methods (TEEdlw) plotted against the means of the two measures (n=17). Mean bias (i.e, TEEpedo – TEEdlw) was – 0.39 MJ, and the mean error (SD of individual differences between TEEpedo and TEEdlw) was 1.71 MJ.

Figure 3. Total energy expenditure (TEE) (mean ±SD) assessed by doubly labeled water (DLW) and predicted from pedometry.

During the eight day study, time series data from the Tc pedometers allowed the physical activities of the test volunteers to be classified into one of four categories (run, walk, NEAT, and no activity). Group means of TEEpedo and TEEdlw were similar (within ±0.13 MJ/day), while the prediction of individual TEE was less accurate. The mean 0.13 MJ/day difference between methods was well within the ±0.81 MJ/day 95% confidence interval, while TEEpedo was, on average, within 1% of TEEdlw. This compared favorably with a study of Hot Shot firefighters where TEE, estimated using a chest pocket physical activity monitor (Manufacturing Technology, Inc, Fort Walton Beach, FL), was predicted within 3% of TEE assessed by DLW [19,20].

The ability to collect time series data using the Tc pedometers, and the ability to define the proportion of time spent in each exercise category (exercise type and intensity) [21] may have been important factors improving the performance of this pedometry method compared to previous studies of TEEpedo [5–7]. The Tc pedometry method provided reasonable estimates of group mean TEE, but it appeared less suitable for predicting individual TEEs, particularly at TEEs in excess of about 14 MJ/day. Especially problematic are the two sailors with the highest TEEdlw measures of 20.07 MJ/day and 19.16 MJ/day, who had TEEpedo measures of only 17.75 MJ/day and 14.51 MJ/day respectively. With TEEdlw in excess of 14 MJ/d, underprediction was evident.

It is possible that individuals with TEEs greater than 14 MJ/day expended energy in non-locomotive ways such as repetitive heavy lifting, a distinct possibility given the confines of shipboard duty. Secondly, movement up and down ramps and ladders, common in the unique environment of the ship may have resulted in unaccounted energy expenditure. The magnitude of this error, that is the contribution to the unexplained variance in the prediction equation, is unknown. Future studies should test the validity of Tc pedometry method in more typical free-living groups of test volunteers where TEEs exceeds 14 MJ/day. This would assess the validity of
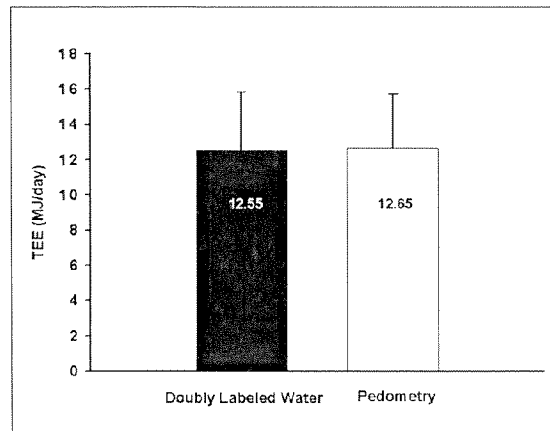
TEEpedo measurement in the range of TEEs that many athletes and military personnel expend during training.

Another possible explanation for the under-prediction at the higher levels of TEE could have been the way the data was captured and saved by the pedometers. The data was saved in as short as 1 – second intervals providing accurate detail in amount of time spent in each activity. However, in the absence of detectable movement, it is possible that no data would be recorded for up to a 30 – min interval. Over the course of an 8 – day study, small errors of not accurately determining precisely when the exercise changed from inactive to active could have multiplied, producing inaccuracies in the prediction model for individuals. The inaccuracies would be more pronounced in those individuals with greater exercise intensities because RMR, which presumably would be accurate, accounts for a smaller proportion of TEE. Furthermore, analyzing the data files to determine the proportion of time spent in each activity became a very time-consuming and laborious task. Future versions of these pedometers should use the internal clock of the pedometer to calculate the proportion of time spent in each mode of activity, permitting more accurate data and more efficient calculation of energy expenditure from the various modes of activity.

CONCLUSIONS

In shipboard sailors, the Tc pedometry method provided accurate predictions of group mean energy expenditures at TEE up to 14 MJ/day. Individual predictions of TEE were less accurate, particularly at TEEs over 14 MJ/day, a level common in soldiers, athletes and physical labor workers. Previous attempts at validating free-living TEEpedo with TEEdlw have met with modest success when performed with elderly patients [5], overweight women [6], and young healthy women [7]. Since TEEs associated with various military operations are not entirely known, and the daily minute-to-minute patterns of energy expenditure in military operational training are not known, further work on pedometry appears justified.

Disclaimer and funding

The opinions or assertions contained herein are the private views of the authors and are not be construed as offi-

cial or as reflecting the views of the Department of Defense. Human subjects participated in these studies after giving their free and informed voluntary consent. The investigators have adhered to the policies for the protection of human subjects as prescribed in Army Regulation 70–25, and the research was conducted in adherence with the provisions of 45 CFR Part 46. Citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement or approval of the products or services of these organizations.

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